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FRONTAL MOVEMENTS CONTRARY TO INDICATED GRADIENT FLOW PRODUCED BY MINOR WAVES

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[Weather Bureau, Washington, May 1938]

During the past 2 years considerable improvement has been effected in the technique of the analysis of synoptic weather maps. There has been a definite trend toward elimination of fronts which show displacements inconsistent with the indicated gradient flow; but historical sequence has been and always must be the basic criterion for the identification of a front. A problem often encountered by the synoptic analyst is the paradox of a surface front for which good historical evidence exists, but which is moving directly against the gradient flow indicated by sea-level isobars.

The basic requirement for a surface front is that an isentropic surface (1) intersect the ground at an appreciable angle. Any air of greater entropy moving along the surface of the earth must therefore rise when it comes in contact with this frontal or isentropic surface. Displacement of such a frontal surface is produced by the component of winds normal to the front, because air cannot blow through an isentropic surface, except by mechanical turbulence over rough terrain. The geostrophic wind velocity component normal to a frontal surface is therefore ordinarily a good indication of the rate of movement of a front.

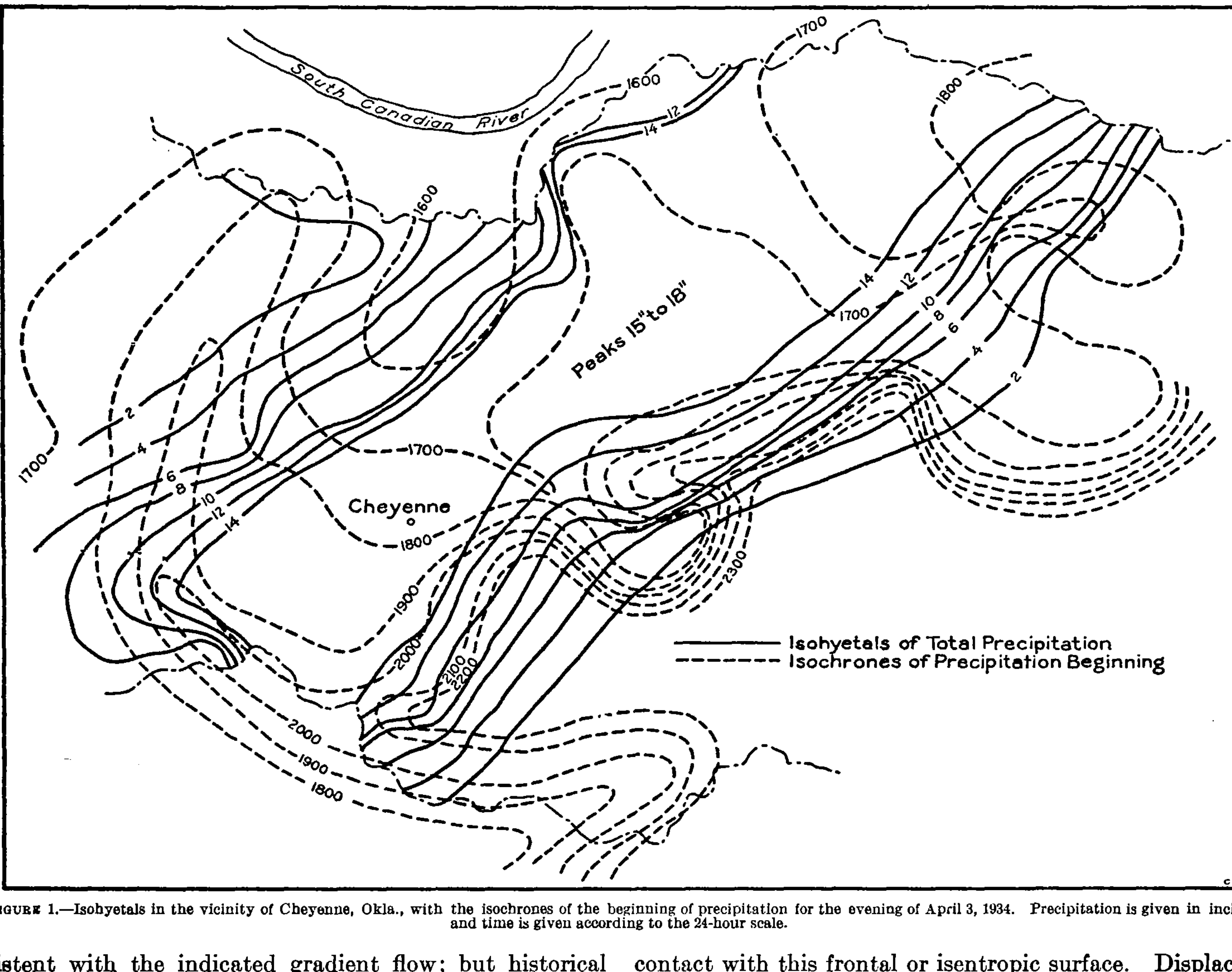


FIGURE 1.—Isohyetals in the vicinity of Cheyenne, Okla., with the isochrones of the beginning of precipitation for the evening of April 3, 1934. Precipitation is given in inches and time is given according to the 24-hour scale.

There is another important force affecting the movement of fronts which is too often neglected. That is the isallobaric component. Brunt and Douglas (**2**), and Petterssen (**3**) have stressed the importance of the isallobaric component in a deepening depression. This component is usually directed towards the center of low pressure and may be in direct opposition to the gradient flow, especially near a warm front. Displacement of a warm front is directly proportional to the component of the cold air away from the front. If the isallobaric component in the cold air is opposite to, and equals or exceeds the component of, the gradient velocity the warm front may be held stationary or move backwards; that is, in the direction it would move if it were a cold front. It is therefore conceivable that a front could move against the indicated gradient.

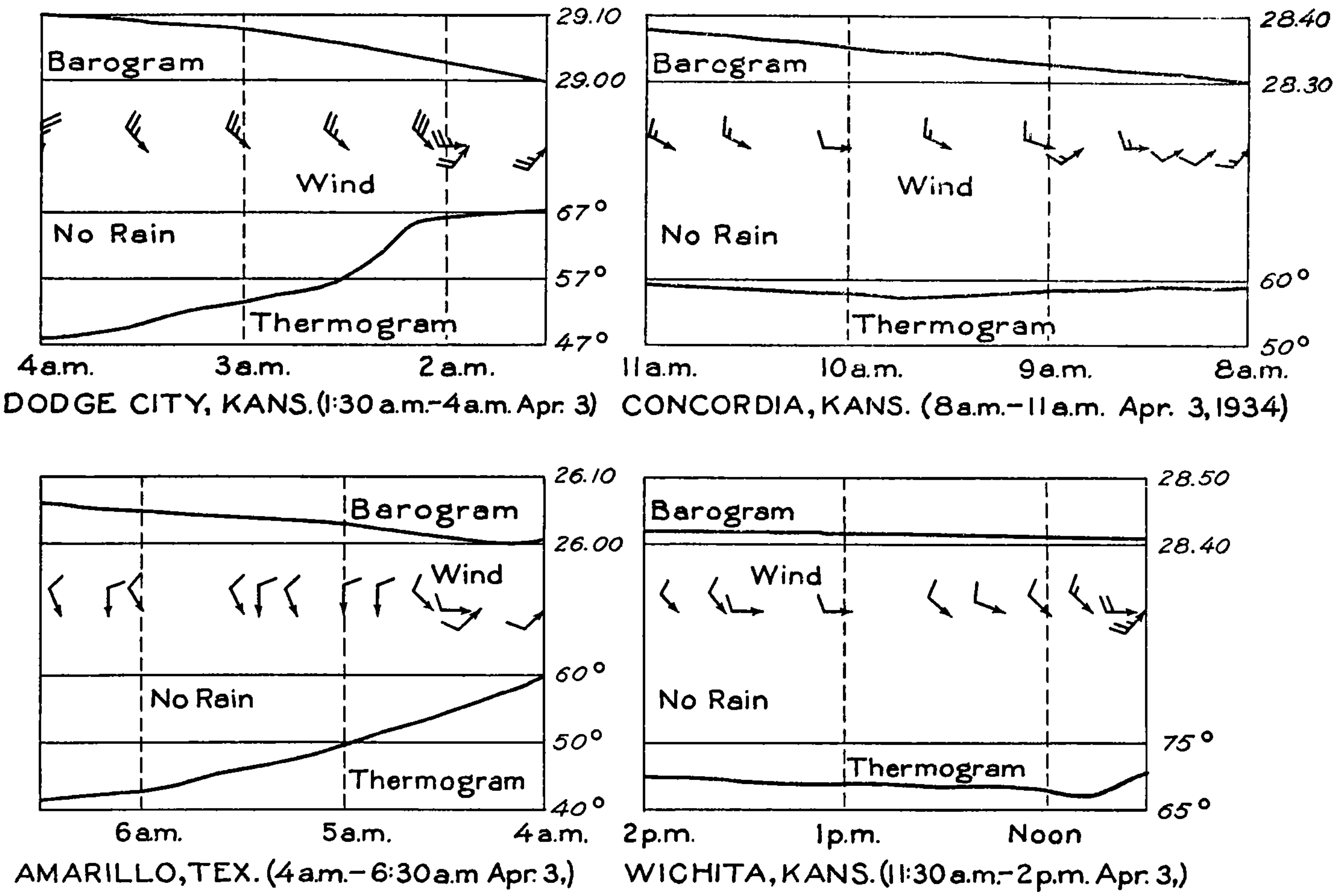


FIGURE 2.

The problem of a cold front extending out to the north or northeastward from a center of low pressure has been particularly troublesome for some time because a cold front in such a position defies the laws of gradient flow. If any front existed in such a position, gradient winds would carry it counterclockwise around the LOW. However, there often appeared to be good historical evidence for frontal activity in such a position, and further evidence for the front remaining in the same relative position while the low pressure center and the trough to the northeastward moved along to the south or southeast. The pressure tendencies in such cases are usually masked by the effects of movement of the pressure system, and appear identical with those of an ordinary front. An easy solution of the problem therefore seems to be to introduce an upper air front in such a region, which is perfectly logical since there is good evidence that upper fronts not only can but do exist north of the surface position of the center of an occluded depression (**4**). However, an upper front not only demands a previous occlusion but also a very sudden increase in the slope of isentropic surfaces aloft. Such an increased slope should be accompanied by definite changes in wind direction and velocity at the level of steepest slope or in other words at the level of the front. These criteria for upper fronts are apparently all fulfilled on some occasions, but some or all of them are not fulfilled in other cases of apparent frontal activity.

In connection with a study of flood-producing storms in Oklahoma the author had occasion to make detailed analyses of several pressure systems with a front north of the center of lowest pressure apparently moving against the gradient flow. The results of this study proved to be of great interest, and seem to suggest a definite solution. The storm of April 1934 which produced very heavy rains in western Oklahoma is a good example of the general type, and a discussion of this storm brings out the significant features:

On the morning of April 2, 1934, and oval-shaped low pressure system was central over northern Colorado. To the north of this system was a mass of polar Pacific air, and south of the center a modified form of polar Pacific air. The surface data seemed to indicate a warm front in central Nebraska and a cold front running from northwestern Nebraska to southwestern Utah. There was

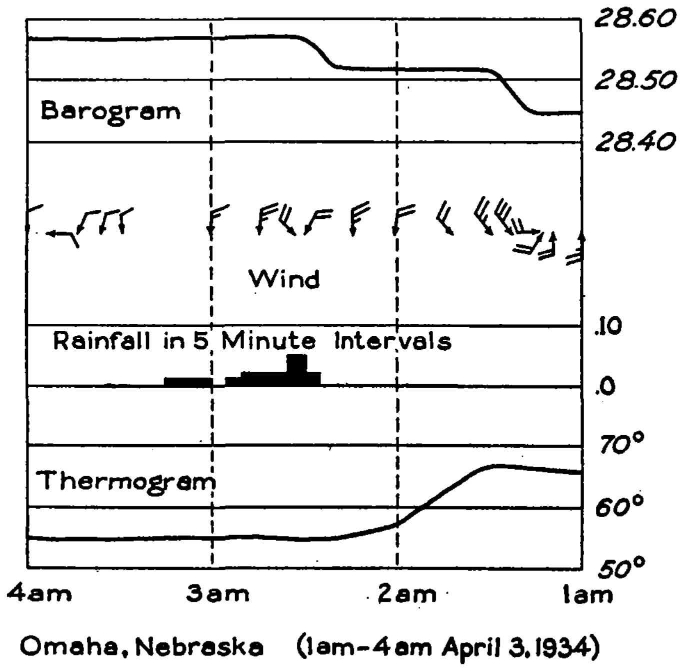
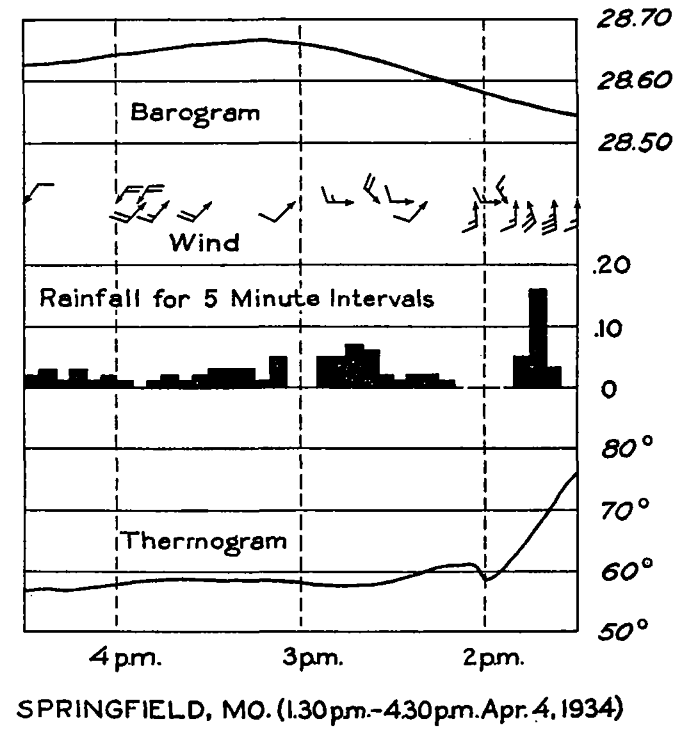


FIGURE 3.



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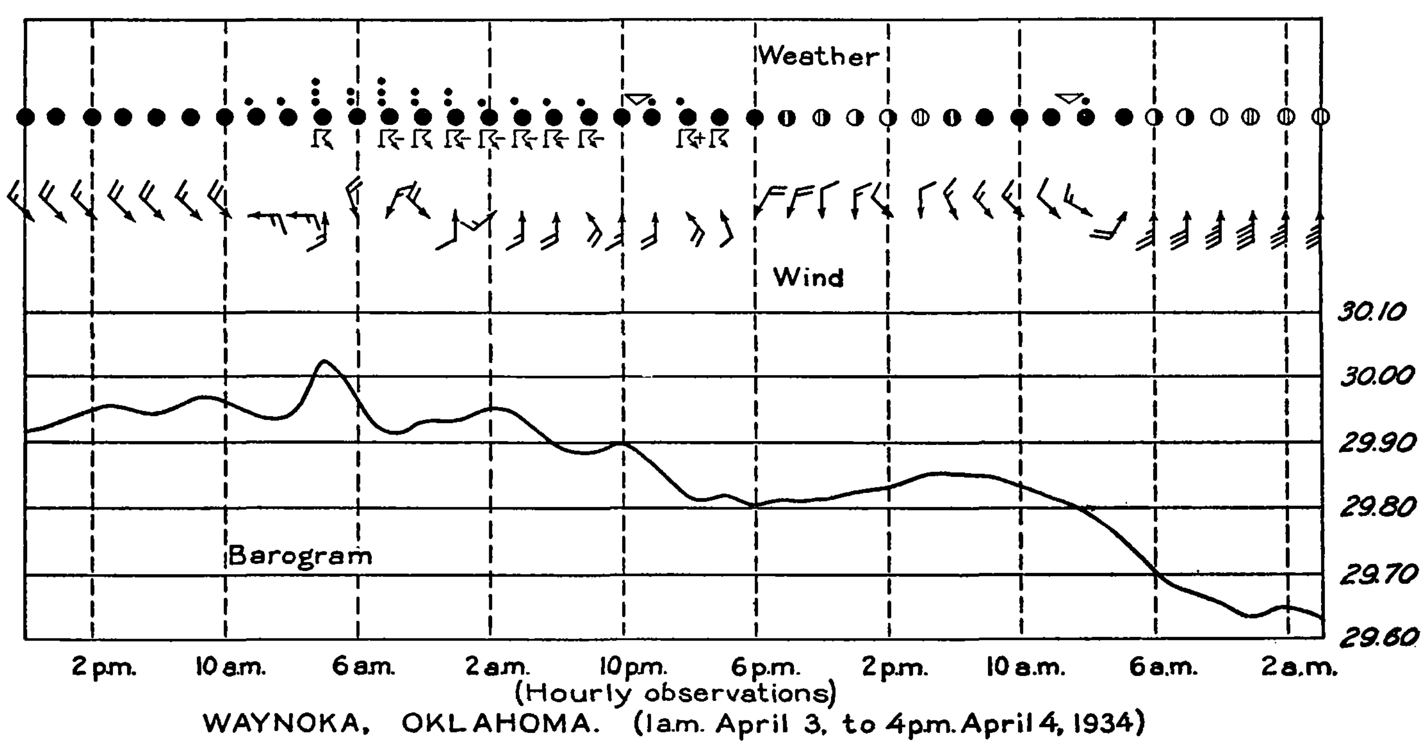
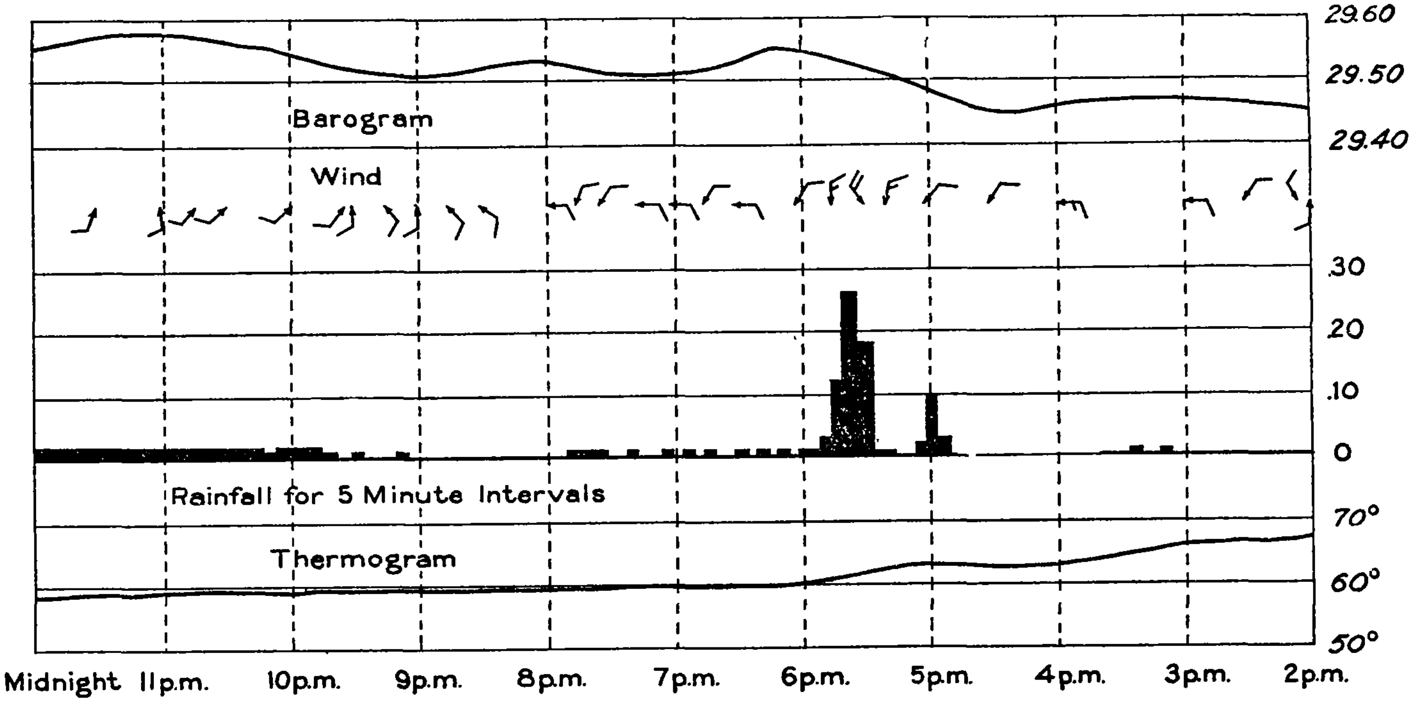
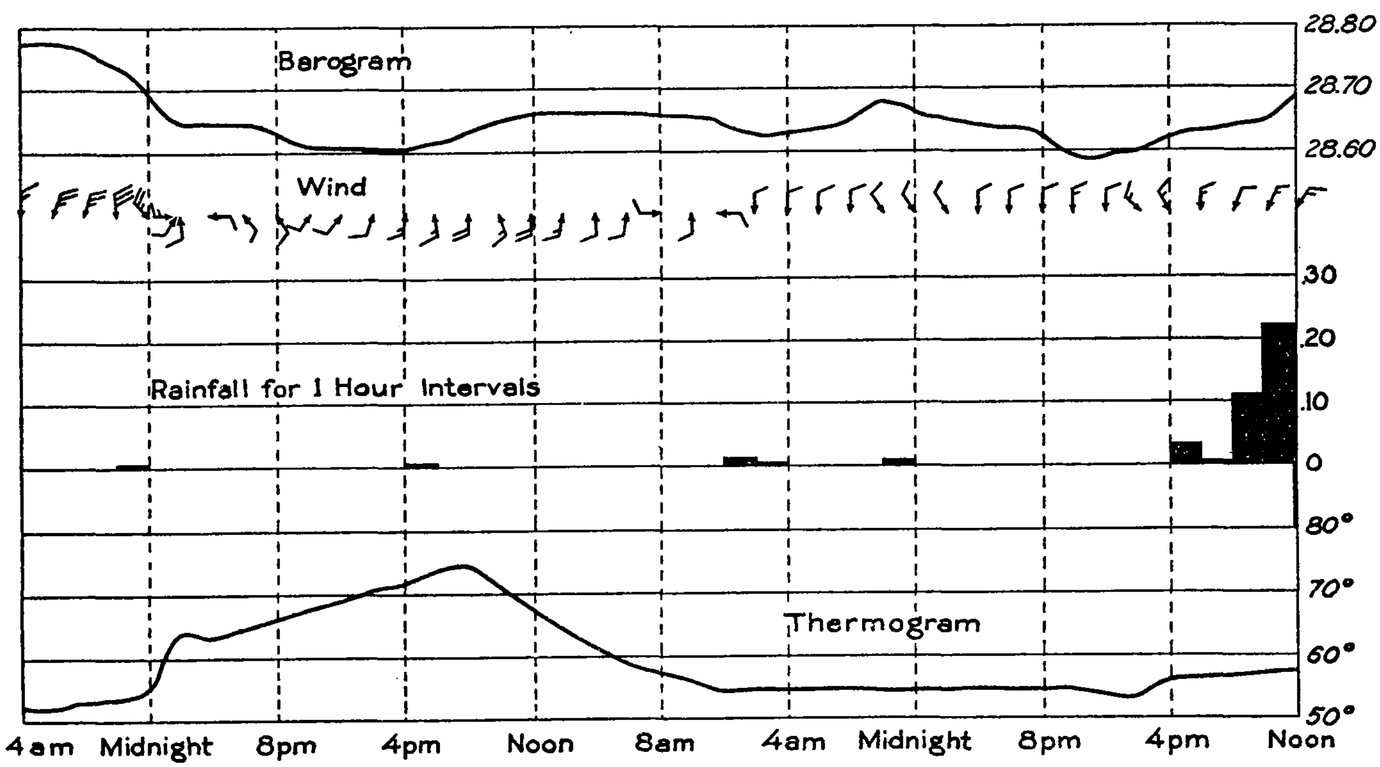


FIGURE 5.



FORT SMITH, ARK. (2 p.m.–12 p.m. April 4, 1934)

FIGURE 6.



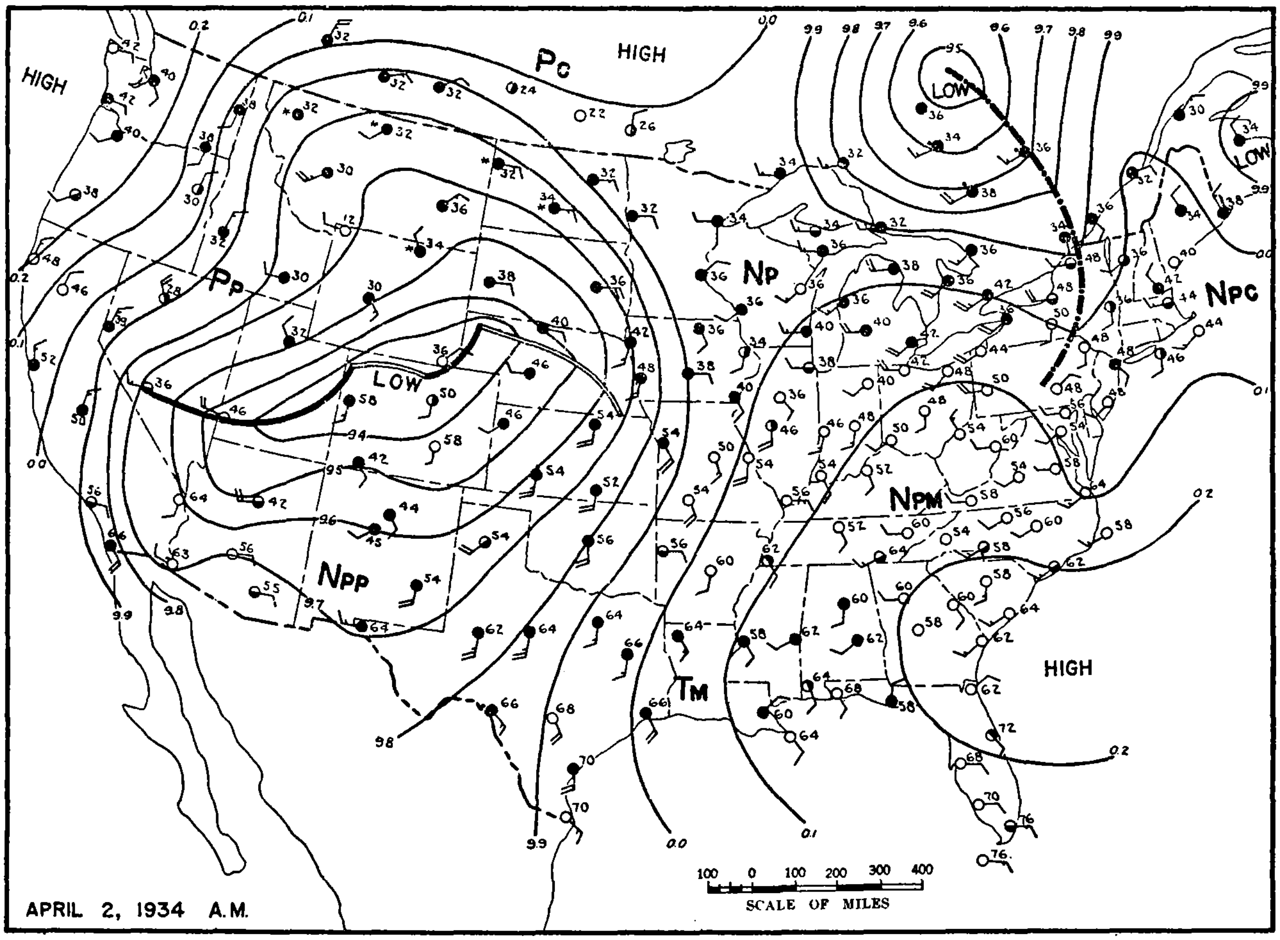
OKLAHOMA CITY, OKLAHOMA (Noon April 4 to 4 am April 6, 1934)

FIGURE 7.

some evidence for a secondary wave in northwestern Colorado. Pressure was rising quite rapidly north of the center, and falling moderately to the south and southeastward. The gradient flow indicated in Nebraska suggested that the warm front in this region should have moved northward. However, on the evening map of the same date it is noted that the entire frontal and pressure system had been displaced to the southeastward. There was still evidence of two waves on the front. The southeastward progression of the frontal system and of the accompanying pressure trough continued to the morning of April 3, 1934.

From this point on, detailed checks were made of the autographic records from a number of middle-western stations. Although the gradient indicated that the front should be a warm front and should therefore have been displaced westward or northwestward, the records show that the front and pressure trough were displaced gradually eastward and southeastward. It might be expected that when a pressure center passed to the south of a station that the change in wind direction through the trough above the pressure center would be from south through east to north. However, it was found that the front not only moved against the indicated gradient flow, but also showed definite frontal characteristics as it passed each station. Graphical reproductions of the autographic records for a number of stations during the passage of the trough and subsequent waves are shown in the accompanying figures. The chart of the hourly observations for Waynoka, Oklahoma, also shows the effects of the frontal and wave passages. In all cases it was found that the wind shifted from south to southwest to west to northwest and finally to north. The autographic records seem definitely to indicate that the frontal system was displaced by means of a series of waves of varying intensity. The passage of the trough and the change in wind direction from south to north were effected by the passage of one or more waves at each station. The heaviest precipitation seemed to occur coincident with the peak of wave activity.

The frontal system not only showed wave activity in Oklahoma and Texas but also in Indiana. The change in wind direction at Indianapolis from southwest at 8:00 p. m. on April 3 to northeast at 8:00 p. m. on April 4 was accompanied by the passage of two minor waves with a definite cyclonic wind shift in both instances. When this frontal system passed through western Oklahoma on the night of April 3–4, 1934, very heavy rains occurred in a short period of time. Eighteen inches in 6 hours fell near Cheyenne, Okla. Moderate to heavy rains and tornadoes were also reported at a number of other stations along the front (5). The frontal system continued its eastward and southward displacement until the morning of April 5, 1934. Its passage to the eastward was identified by means of autographic records for stations in the Mississippi Valley. All these stations seemed to further indicate the displacement by means of a series of minor waves. The records



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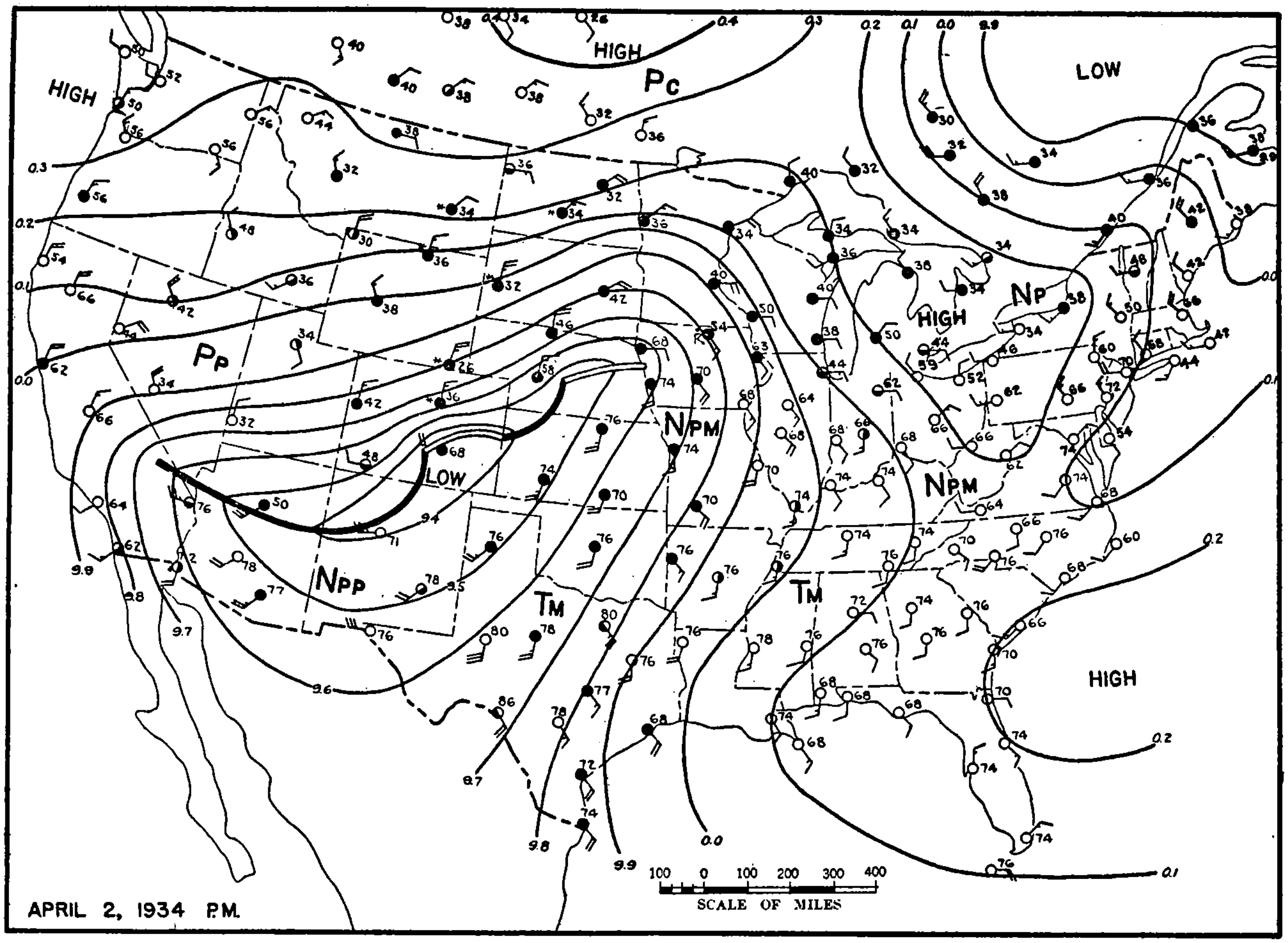

FIGURE 9.

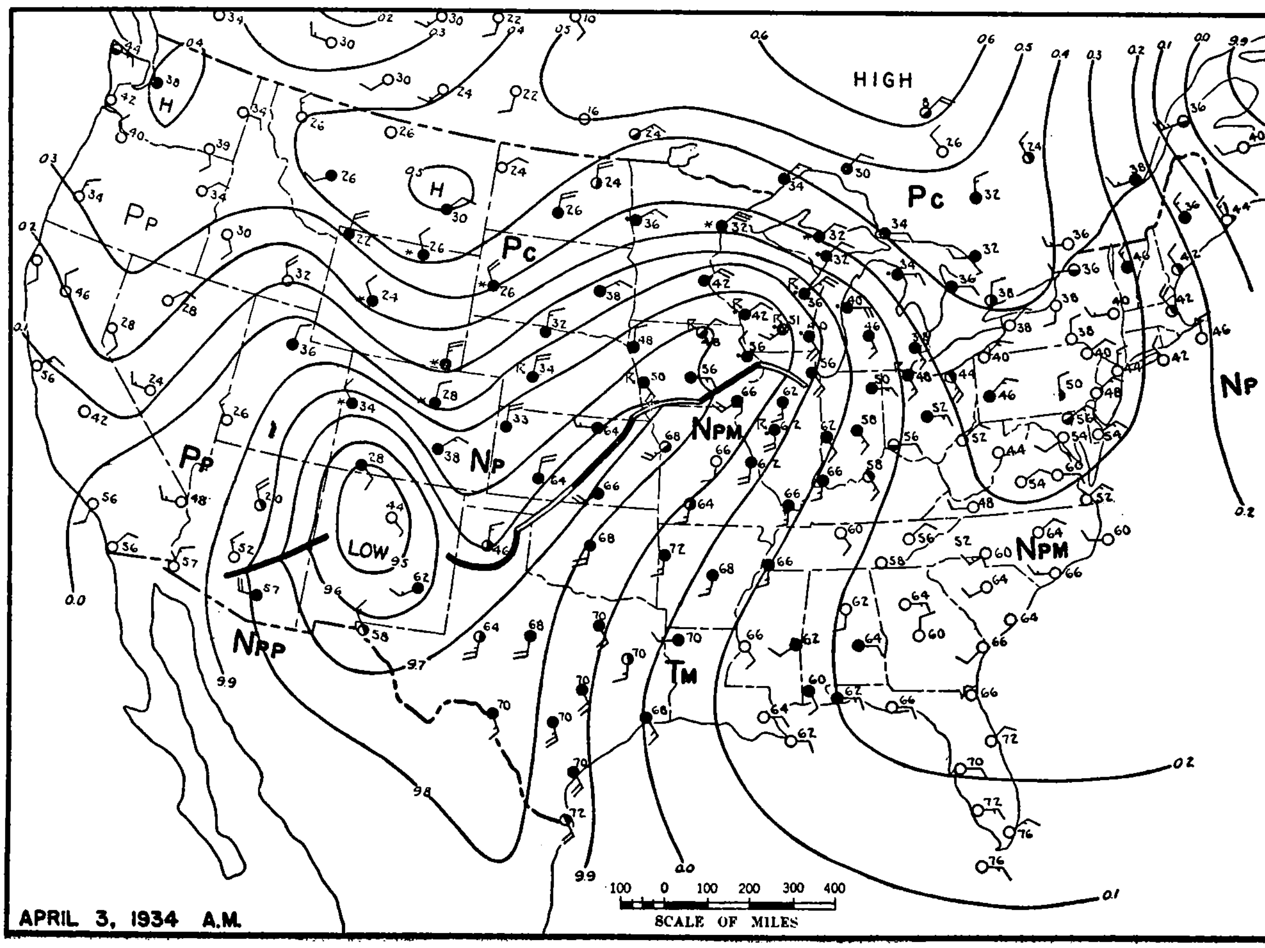

FIGURE 10.

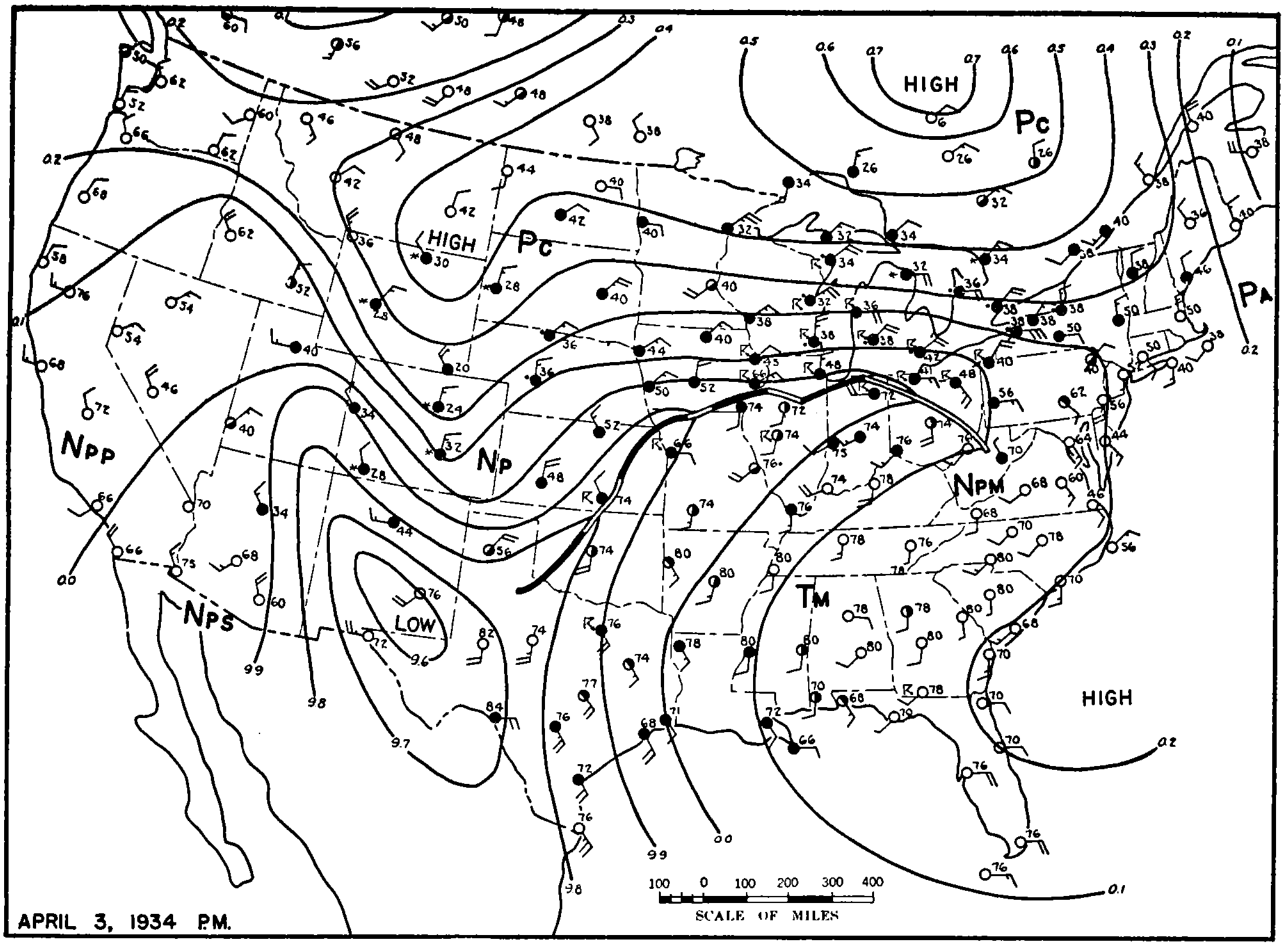

FIGURE 11.

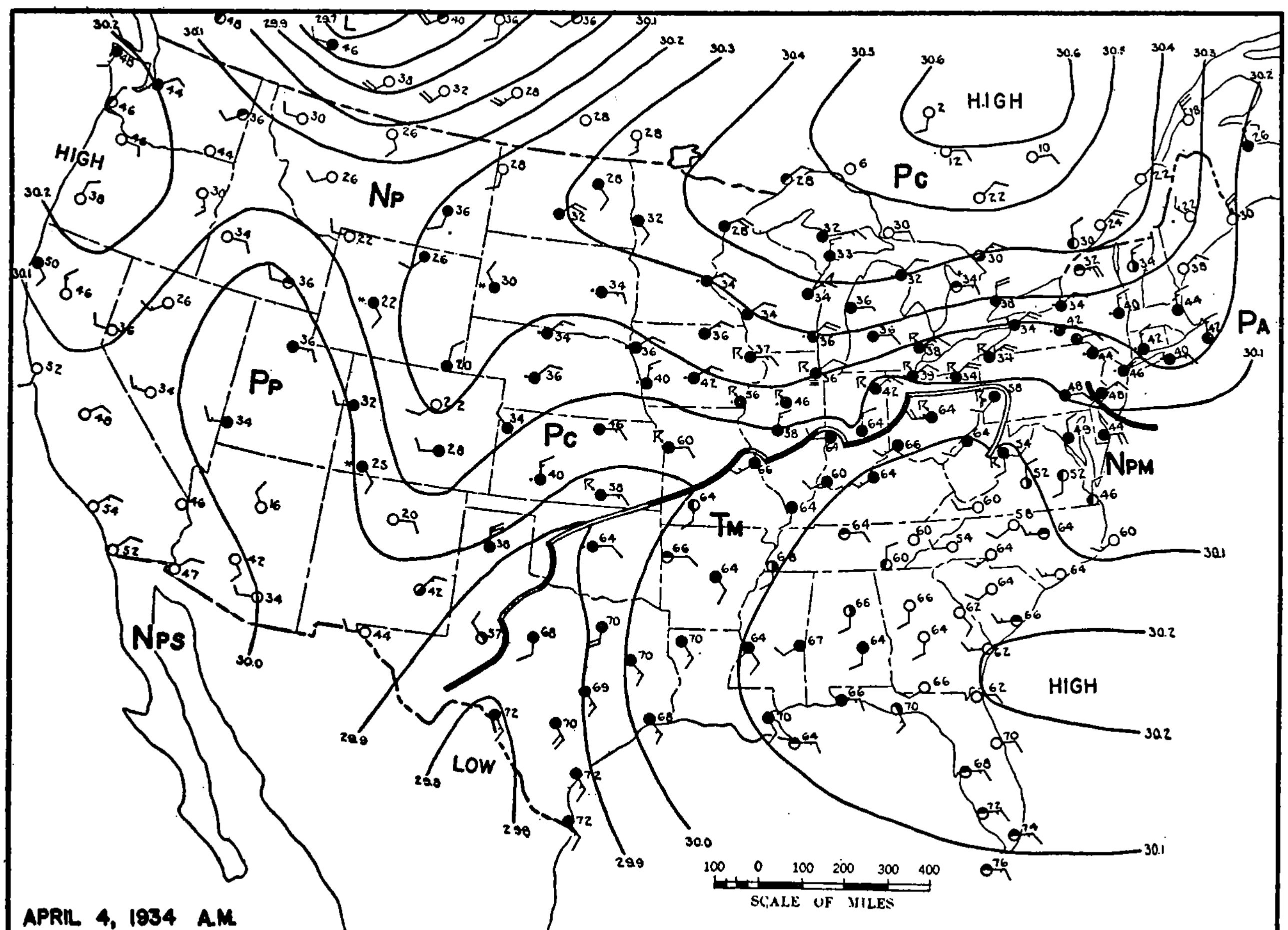

FIGURE 12.

indicate that some of these waves may have been very intense although of small amplitude. Pilot-balloon data for this period do not seem to support the presence of an upper front.

Several other storms studied in connection with floods in this region seem also to show this pronounced wave activity, and it is therefore concluded that such storms are to support the idea of a front being displaced by means of a series of minor waves. An examination of the file of charts showed that an ordinary cold front does not have such pronounced wave action. Detailed charts of an ordinary front passing through Ohio showed a very regular progression of the wind shift and accompanying precipitation.

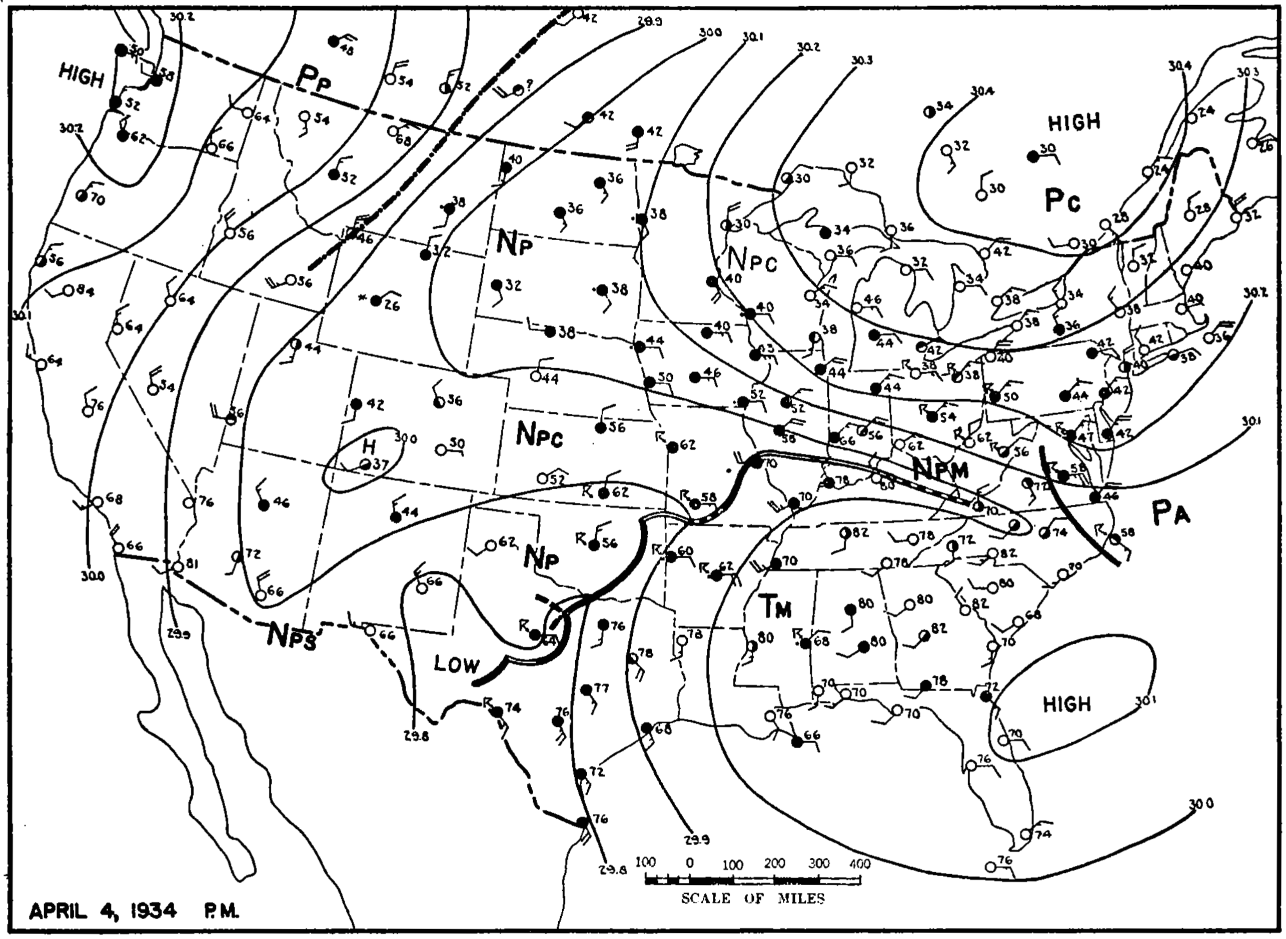

FIGURE 13.

very significant in producing flood rains. The reason for this appears to be that the front is displaced quite slowly, principally by means of the isallobaric component and may therefore be relatively stationary over one region for a prolonged period. The southward or eastward displacement of the front can only be accomplished by means of small waves and these waves may become intense and produce heavy rains.

A study by Thornthwaite of a storm in Oklahoma on May 1, 1936, is also a good example of a front being displaced against the indicated gradient flow **(6)**. Reference to his detailed charts for a small region shows that the wind shift lines were very irregular. This seems further

The explanation for the unusual behavior of fronts north of LOW centers seems to be in the effects of the isallobaric component. A definite explanation of the causes and effects of areas of rising and falling pressure cannot be made until more is known of the general circulation of the atmosphere. However, the existence of anallobars and katallobars must be accepted, even if they are not adequately explained. If the pressure tendency fields are out of balance with the displacement of isobars there must be an additional motion developed to maintain a balanced state. The motion that develops is that due to the isallobaric component. The isallobaric component is directed from the anallobaric center toward the katallobaric center and its magnitude is proportional to the isallobaric gradient.

In a low-pressure trough extending northeastward from a cyclonic center, two opposing forces may develop. First, the component due to gradient flow, directed from south to north, and second, the isallobaric component directed from north toward south. The resultant motion tends to sharpen the temperature contrast along the trough, and more and more isentropic surfaces are crowded into a small area. The opposing forces represent an unbalanced state, and there must be a continuous breaking down by means of minor waves. Since the isentropic surfaces have become crowded, and motion in the lower surfaces is directly opposed to those in the higher surfaces, the resultant vertical velocities will be greater than normal for the warmer air. The potential energy of mass distribution may therefore very rapidly be converted into kinetic energy and the resultant wave action may be quite intense. If additional energy is provided by release of the latent heat of condensation severe local storms may develop. Such storms cannot attain very great magnitude because their continued development is opposed by the major depression.

Because of the direction of the isallobaric component, and further because of the greater density of the cold air, the passage of each minor wave results in a southerly or easterly displacement of the mean position of the front. The front at any point will recede but little with the passage of the next wave and the front therefore is gradually displaced eastward and southward directly against the indicated gradient flow.

This type of storm is considered of great importance, not only for flood studies but also for short-period airways forecasting; and it is believed that a rigid analysis will identify these very small waves. Such an analysis should not only prove interesting but also very helpful to the forecaster. The immediate indications of the movements of minor waves would be their behavior in the last hour. The general trend of the pressure trough and frontal system can be deduced from the magnitudes and displacements of the isallobaric systems.

(1) Rossby, C. G., Isentropic Analysis. Bulletin American Meteorological Society, vol. 18, June–July 1937.

(2) Brunt and Douglas, Memoirs of the Royal Meteorological Society. 3 No. 22.

(3) Petterssen, S., Kinematical and Dynamical Properties of the Field of Pressure with Application to Weather Forecasting. Geofysiske Publikasjoner, vol. 10, No. 2, 1933.

(4) Lichtblau, Stephen, Upper-Air Cold Fronts in North America. MONTHLY WEATHER REVIEW, December 1936.

(5) Monthly Climatological Data, Oklahoma Section, April 1934, vol. XLIII, No. 4.

(6) Thornthwaite, C. W., The Life History of Rainstorms. Geographical Review, vol. XXVII, No 1, January 1937.

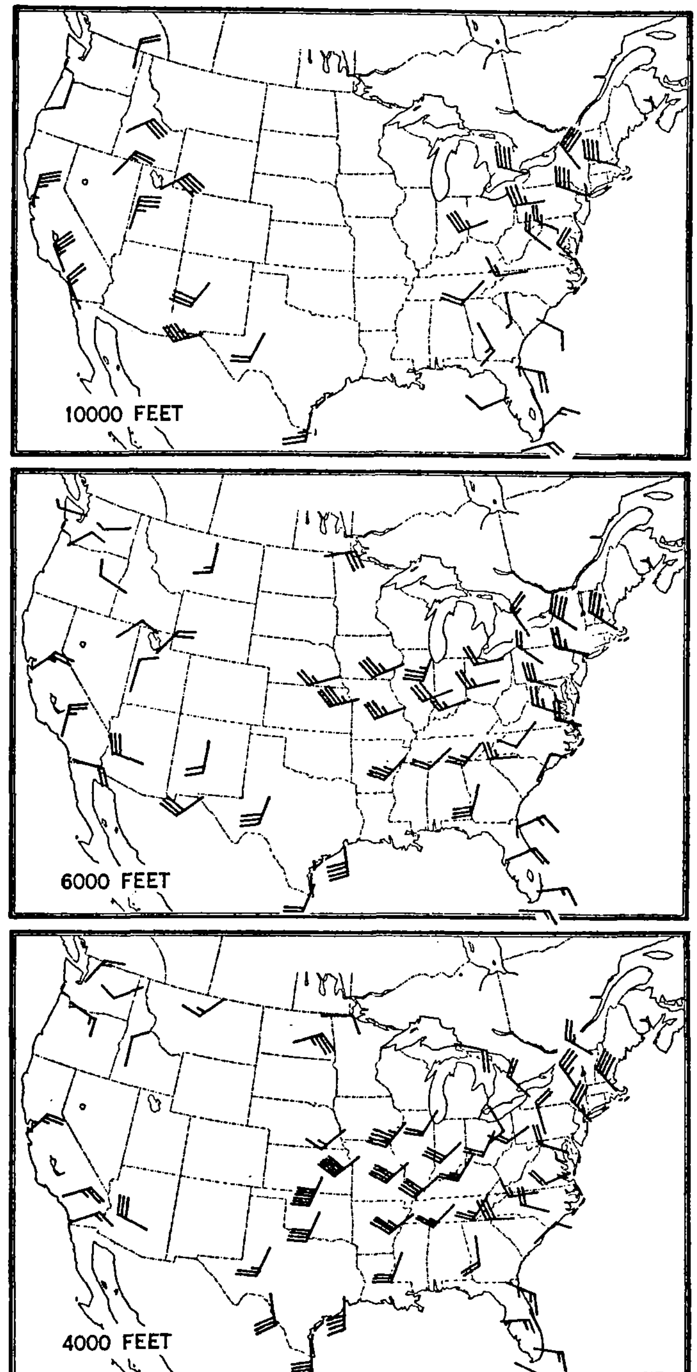

FIGURE 14.—Upper-air wind velocities at the morning observation on April 3, 1934.

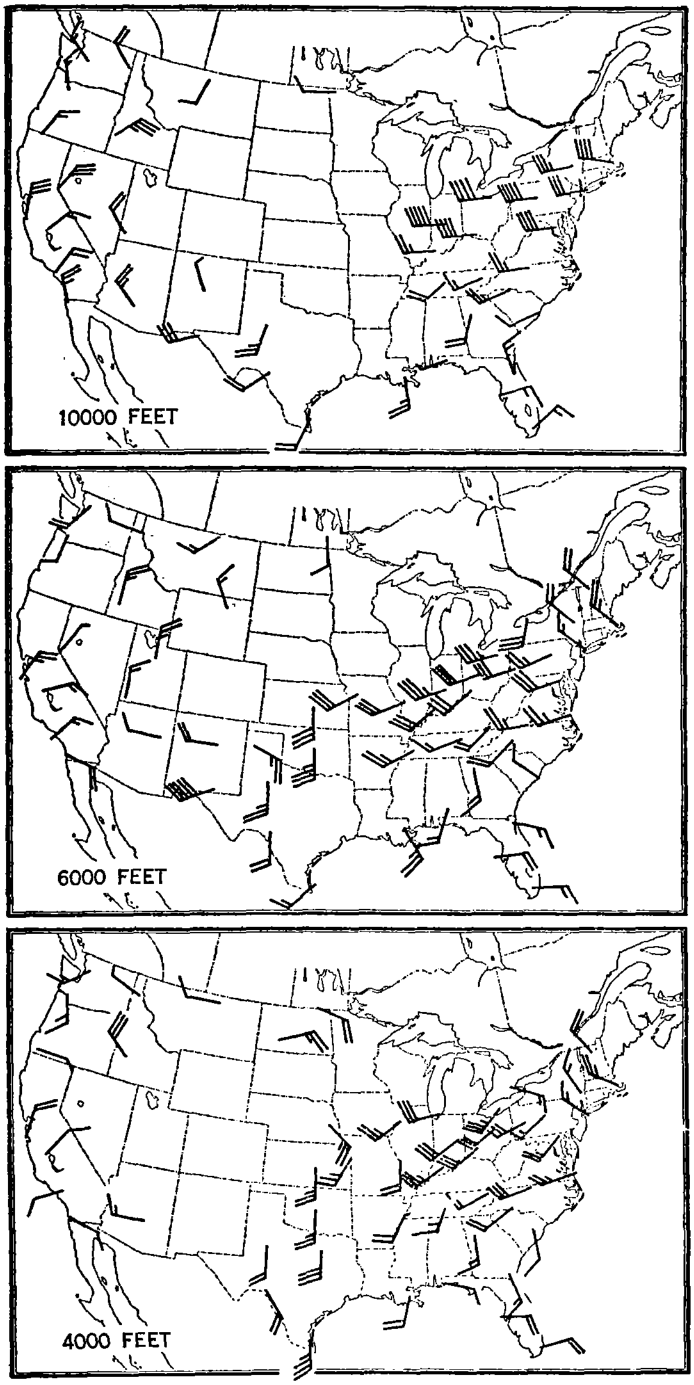

FIGURE 15.—Upper-air wind velocities at the evening observation on April 3, 1934.

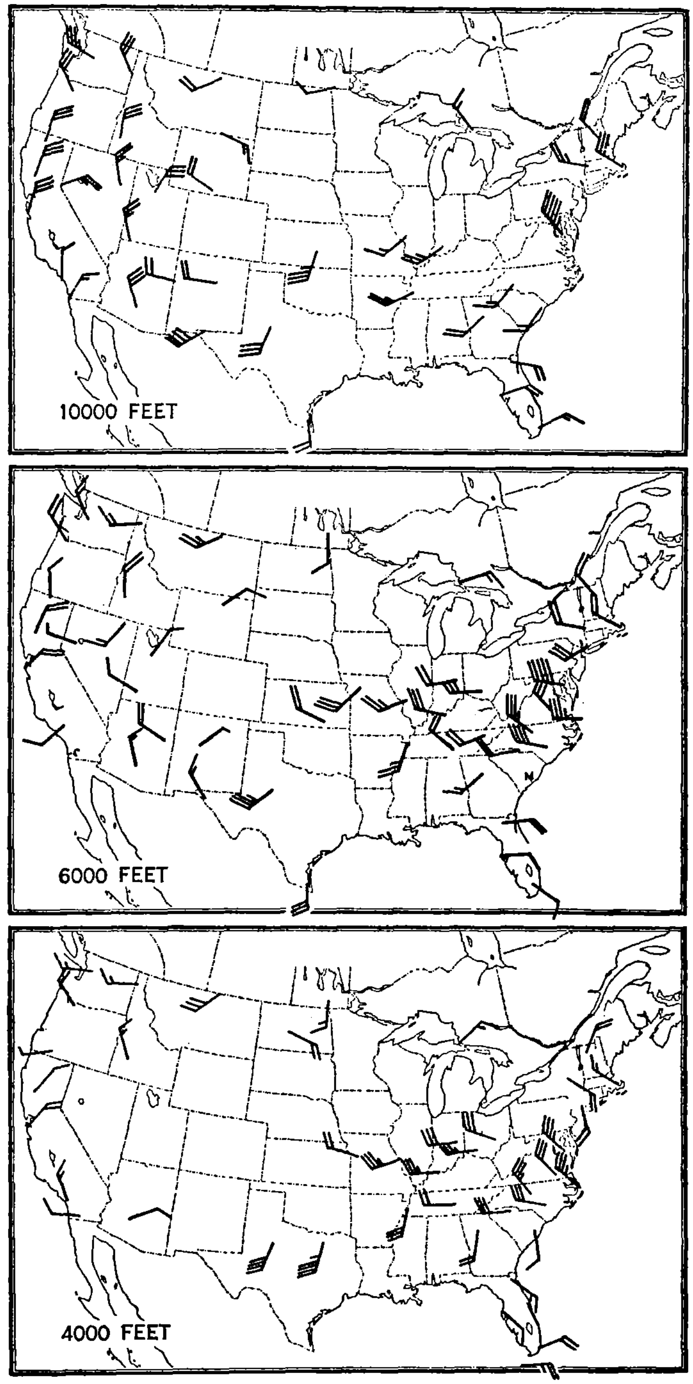

FIGURE 16.—Upper-air wind velocities at the morning observation on April 4, 1934.